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SENSITIVITY OF AUDITORY AND VESTIBULAR SYSTEMS TO STIMULI OTHER THAN SOUND AND MOTION

Kenneth D. Fisher, et al

Federation of American Societies for Experimental Biology

Prepared for:

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There is evidence to suggest that auditory and vestibular systems can be stimulated by forms of energy other than sound, gravity and motion. This report reviews the evidence related to such sensitivity, and indicates the potential importance of enhanced sensory capabilities. Suggestions for future research on the response of the auditory and vestibular systems to additional environmental stimuli are presented.

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FOREWORD

The Life Sciences Research Office (LSRO), Federation of American Societies for Experimental Biology (FASEB), provides scientific assessments of topics in the biomedical sciences. Reports are based upon comprehensive literature reviews and the scientific opinions of knowledgeable investigators engaged in research in specific areas of biology and medicine.

This technical report was prepared for the Human Resources Research Office, Defense Advanced Research Projects Agency (DARPA), Department of Defense, under contract number F44620-74-C-0077 monitored by the Air Force Office of Scientific Research.

The report has been reviewed and approved by the LSRO Advisory Committee (which consists of representatives of each constituent society of FASEB) under authority delegated by the Executive Committee of the Federation Board. Upon completion of these review procedures the report has been approved and transmitted to DARPA by the Executive Director, FASEB.

While this is a report of the Federation of American Societies for Experimental Biology, it does not necessarily reflect the opinion of all the individual members of its constituent societies.

C. Jelleff Carr, Ph. D.
Director
Life Sciences Research Office

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SUMMARY

There is evidence to suggest that the auditory and vestibular systems can be stimulated by forms of energy other than sound, gravity and motion. This report reviews the evidence related to such sensitivity, and indicates the potential importance of enhanced sensory capabilities. Suggestions for future research on the response of the auditory and vestibular systems to additional environmental stimuli are presented.

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I. STATEMENT OF THE CONCEPT

Infrasound influences the sensory response of the auditory system; similarly, ultrasonic stimulation occurs as a component of speech and certain types of noise. Initiation and transmission of responses to such stimuli by nerve fibers of the auditory system have been suspected but are unproven. There is some evidence to suggest that ultrasonic stimulation of auditory nerve fibers may constitute an arousal response, focusing attention on potentially dangerous environmental stimuli. Possibly stimulation by nonionizing electromagnetic energy could function similarly.

Linear and angular acceleration stimulate the vestibular apparatus. Central nervous system vestibular mechanisms apparently play a role in modulating the level of total sensory input and the level of motor output during the periods of intense excitement of schizophrenic patients and autistic children. These observations suggest that the vestibular organs may be involved in the development of normal functioning of sensorimotor integration processes. It is possible that stimulation of the vestibular apparatus by forces other than motion may be involved in these processes.

Interactions among the several sensory receptor systems of man are well known. The visual system has been studied in great detail, and the neural pathways interconnecting visual centers to other sensory and motor processes are relatively well established. The sensation of head motion or tilt as well as the sensation of whole body motion can be induced visually. Observation of peripheral rotating or moving scenes results in sensations of motion, usually in the opposite direction (Young *et al.*, 1975). Similarly, the neural tracts of the taste organs and the auditory apparatus interact (Benjamin *et al.*, 1965). Despite these observations concerning interactions among the several senses, there has been little work on sensitivities of the vestibular apparatus and the auditory system to forms of stimuli other than sound or motion.

This report reviews the evidence related to possible sensitivity of the auditory and vestibular systems to stimuli other than sound, gravity and motion. If the concept is valid, then reception and perception of other environmental stimuli may be important in performance and survival. Because military and civilian populations are continually exposed to several forms of infrasonic, sonic, ultrasonic and nonionizing electromagnetic energy from equipment and weaponry, it is of interest to explore the possibility that the auditory and vestibular receptor systems may be activated by other forms of energy.

II. STIMULATION OF THE AUDITORY SYSTEM

A. INFRASONIC, SONIC AND ULTRASONIC STIMULI

Disciplinary separation of fields within acoustic science is related to the frequency range of the human auditory system. The audio-frequency range is 16 to 20,000 Hz. Frequencies below 30 Hz are considered to be in the infrasonic region, although airborne acoustic energy at 200 Hz or below is considered by some investigators to be infrasonic. Strict interpretations of ultrasonic acoustic energies restrict the definition to frequencies above 20,000 Hz, although some ultrasonic sources have frequency components of 10,000 to 20,000 Hz (Goldstein and Sinskey, 1969).

Stimulation of the auditory system by sound in the audio-frequency range produces nonaural effects, specifically alterations in physiologic or psychologic state (Cohen, 1969). Kryter (1970) has suggested that the auditory system is organized into primary and secondary neural pathways. The former consist of sets of afferent pathways that transmit impulses generated by mechanical stimulation of the inner ear by sound waves. The secondary neural pathways are less well defined, and consist of axonic connections from synapses in the primary system to reflex centers in the brainstem and activating-regulatory centers of the midbrain. Impulses reaching the reticular formation may spread to higher cortical centers that influence alertness, cognition and coordination of perceptual-motor activities. In addition, neural interconnections with the autonomic nervous system occur at these levels. Audible sound stimulation is known to affect some aspects of cortical perception of vision, balance, touch, and olfaction. Some investigators believe stimulation and response of senses other than the auditory system by sound are of little practical significance, while others suggest the preliminary observations indicate need for further study (Cohen, 1969; Kryter, 1970).

The influence of infrasonic and ultrasonic stimulation on both primary and secondary pathways in the auditory system is not well understood. Using experimentally generated infrasonic noise fields of measured frequency, intensity and duration, Mohr *et al.* (1965) found that the most noticeable responses were nonauditory. For example, chest vibration, gagging, respiratory rhythm changes, and diminished visual acuity due to eyeball vibration were observed in trained subjects exposed to broad-band and narrow-band noise patterns with center frequencies of 2 to 50 Hz. No shifts in auditory thresholds were detected after exposures of at least 2 minutes to 142 to 153 dB narrow-band noise with center frequencies of 2 to 10 Hz. However, at all exposures in excess of 130 dB, eyeball, throat, and chest

vibration produced observable decrements in visual acuity and voice communication. These two phenomena may have operational significance in high intensity infrasonic noise fields, but may be related directly to body vibration alone rather than to stimulation of auditory nerve fibers *per se*.

Acoustic frequencies above the range of normal adult hearing border on ultrasound; in addition, the subharmonics of frequencies around 20,000 Hz fall into the audible range. Airborne ultrasonic frequencies are often an unrecognized or unmeasured component of broad-band noise fields containing lower frequencies that extend well into the auditory range. There is some evidence that ultrasound is a normal, but usually undetected, component of human speech (Mason, 1968).

When jet aircraft were first introduced, there was wide-spread anxiety that jet engine noise would include sufficient ultrasonic noise to be harmful to man (Parrack, 1966). However, ultrasonic waves are absorbed rapidly by air and are propagated only a short distance. Thus, high-intensity ultrasonic wavefields are a problem only when the individual is very close to the source; at such proximities, audible noise levels in jet aircraft would be intolerable (Guignard, 1965a).

Goldstein and Sinskey (1969) reviewed the health hazards of ultrasonic energy; all but a few of these investigations involved liquid or solid coupling of the ultrasonic transducers to the experimental animal or human subject. The low acoustic impedance of air results in rapid power loss as the ultrasonic sound-wave field is propagated from the source of ultrasonic energy. Energy is dissipated primarily as heat but the sound pressure level (SPL) threshold for human injury from heat dissipation is approximately 175 dB. These authors stated that death would occur at about 180 dB because the body cannot dissipate heat energy as rapidly as the ultrasound would heat the body. Such excessively high intensities of ultrasonic energy are not encountered in industrial or military situations. Goldstein and Sinskey (1969), as well as Parrack (1966), concluded that airborne ultrasonic SPL up to 140 dB are essentially harmless because of attenuation in the air medium.

Knight (1968) studied industrial equipment generating ultrasonic wave fields and concluded that exposures to several durations and intensities were not hazardous to the vestibular or auditory systems, although subjective effects were often reported. Acton (1968), commenting on these conclusions, reported no significant temporary threshold shift (TTS) in hearing of subjects exposed to 110 dB in one-third octave bands centered at 20,000 and 25,000 Hz.

In a related study, Acton and Carson (1967) suggested that subjective effects of ultrasonic frequency exposures above 70 dB were related to attendant high levels of audible noise rather than to the ultrasonic frequencies alone.

Parrack (1966) had previously concluded that various subjective effects were psychosomatic and related to apprehension. However, Kryter (1970) has pointed out that TTS does occur in subjects exposed to 16,000 to 20,000 Hz in excess of 78 dB. Also, he noted that adverse subjective effects were more evident following ear-damaging exposures to ultrasonic frequencies, than following equally damaging exposures to broad-band noise at audible frequencies.

Parrack (1966) indicated that ultrasound was not a hazard until SPL exceeded 140 dB. Acton (1968) suggested that TTS could be prevented and subjective effects minimized if exposures were limited to SPL of 75 dB in one-third octave bands centered at 8,000 to 16,000 Hz or 110 dB at 20,000 to 31,500 Hz. It is doubtful that military equipment such as high-speed machinery or helicopter turbines generate such levels of ultrasound. However, most studies of noise spectra of military equipment do not include measurement of frequencies over 10,000 Hz (Gasaway, 1969; Gasaway and Hatfield, 1963). Additional information is needed on the frequencies and intensities of ultrasound generated by military equipment and their effects upon the auditory system *per se*. Several observations suggest that specific effects of exposure to ultrasonic energies should be studied in man and experimental animals: specifically, 1) ultrasound may be a normal speech component, 2) there are conflicting data on TTS induced by ultrasonic frequencies, and 3) adverse subjective effects do occur from exposure to ultrasonic stimulation. These investigations should include the effects of ultrasonic energy on the basilar membrane, organ of Corti, cochlear hair cells, and auditory nerve fibers.

B. NONIONIZING ELECTROMAGNETIC RADIATION

Within the spectrum of nonionizing electromagnetic radiation (1 to 10^{20} Hz), the microwave range (100 MHz to 300,000 MHz) has attracted considerable interest in biology and medicine. Microwave fields are generated by a wide range of military, industrial, scientific, and consumer equipment and products, including radar equipment, diathermy machines, kitchen appliances, radio transmitters, and other electronic devices.

The effects of nonionizing electromagnetic radiation on biological systems and on man have been studied in considerable detail in the past two decades (Glaser, 1971; Michaelson, 1974; Tolgskaya and Gordon, 1973). Michaelson (1974), in his comprehensive review, concluded that absorbed electromagnetic energy in the microwave range is transformed into an increased kinetic energy of the absorbing molecules. The increased kinetic energy of the molecules in the tissues produces a thermal effect, resulting

in transient or sustained heating. In most cases, microwave radiation of this type is absorbed by the dermal tissues producing measurable temperature increases. Michaelson (1974) suggested that nonthermal effects might occur, but the evidence was not convincing.

Tolgskaya and Gordon (1973) reviewed the Russian literature on effects of exposure to electromagnetic fields in the radiofrequency band (0.03 MHz to 300,000 MHz). They concluded that most frequencies induce some form of hyperthermia which may be transient or lethal depending upon the wavelength, phase, powerflux, density or duration of exposure. The sensory nerve fibers of the skin and visera appear to be the receptors most affected by this type of nonionizing irradiation.

Exposure to electromagnetic radiation of shorter wavelengths, e.g., microwave radiation of 1.0 mm (approximately 10^{10} Hz) or less, also affects dermal and visceral sensory nerve fibers. Tolgskaya and Gordon (1973) suggested that 1.0 mm radiation is absorbed in the dermal layers while longer wave irradiation may penetrate more deeply, causing degenerative changes in abdominal, thoracic, or cranial organs and tissues. In discussing effects upon specific neural receptors, the authors do not mention reception of electromagnetic stimuli by the vestibular or auditory apparatus.

Frey (1962) observed that humans perceive sounds when exposed to low-power radio-frequency (rf) energy fields. The perceived sound, characterized as "hisses," "buzzes," or "clicks," could be elicited by average incident power levels considerably below those known to induce thermal effects. Subsequent studies have established that auditory effects can be evoked in humans and animals by many frequencies of pulsed microwaves with average power densities as low as 0.4 mW/cm^2 and peak power densities as low as 267 mW/cm^2 (Frey and Messenger, 1973).

Frey and Messenger (1973) observed that loudness of the sensation appeared to be proportional to peak power densities. However, Guy *et al.* (1975) indicated that the threshold of sensation from rf energy is proportional to energy per pulse. Foster and Finch (1974) recorded audible sounds termed acoustic transients in water exposed to microwave radiation. They suggested that "hearing" elicited by microwave exposure is due to thermal acoustic stimulation within the ear and implied that transient thermal stimulation of cochlear fluid was involved.

Recently, Guy *et al.* (1975) concluded that the threshold for microwave pulse-evoked auditory sensations was related to incident energy per pulse. They measured a human threshold of 40 $\mu J/cm^2$ with pulses 30 μsec wide, an energy density which would produce tissue temperature increases of approximately 5×10^{-6} °C. Destruction of the cochlea or removal of the cochlear fluid of cats resulted in total loss of evoked potentials due to microwave stimulation suggesting that microwaves were interacting with the

high-frequency detecting sensory cells of the cochlea. They concluded that the most likely cause of the conversion of electromagnetic energy to acoustic energy was probably the minute thermal expansion forces generated in the cochlea. That such transductions could occur at temperature changes as low as 5×10^{-6} °C is remarkable and reflects the extreme sensitivity of the auditory system.

Lebovitz (1975) indicated that there is more than enough energy in low levels of microwave radiation (1 mW/cm^2) to affect the nervous system if an appropriate and efficient transducing organ or tissue could be specified. He suggested that pulse-modulated microwave radiation may induce phasic displacement of the tympanic membrane, resulting in auditory stimulation. The exact nature of acoustic nerve stimulation from low power densities of microwave radiation requires further study and clarification (Guy, 1975). Regardless of the nature of the causal mechanism, the fact that the auditory apparatus can respond to microwaves is in itself significant. The pathophysiological aspects of this phenomenon as well as the possible existence of a defense arousal response should be determined.

Finally, man has been intrigued by the possible existence of extrasensory perception for many years. The nature of the stimuli and the specific receptors in the body have never been adequately identified. It is of tangential interest to note that Targ and Puthoff (1974) have attempted to conduct laboratory studies on transference of information between individuals under conditions of visual, auditory and electromagnetic shielding. While these laboratory studies have been criticized extensively (Anonymous, 1974), there is some circumstantial evidence to suggest that microwave stimulation of the auditory apparatus might be involved.

III. STIMULATION OF THE VESTIBULAR APPAPATUS

A. INFRASONIC, SONIC AND ULTRASONIC STIMULI

There is a vast literature on the biomedical effects of vibration (1-30 Hz), properly termed mechanically-coupled infrasonic frequencies (Guignard, 1965b; Hornick, 1973). However, in this situation, mechanical contact between vibrating solids or liquids and the body gives rise to resonant vibration in organs and body cavities. There is less known about actual stimulation of the vestibular apparatus by sonic or ultrasonic energy.

Lackner and Graybiel (1974) have reported that obvious vestibular responses were induced by application of a physiotherapy vibrator to regions of the skull. With such treatments visual and postural illusions, nystagmus, and motion sickness were induced in subjects held in a stationary or rotating environment. The authors indicated canalicular stimulation probably resulted from transfer of the infrasonic stimulus through the skull.

Balance and equilibrium of normal adults were impaired when subjects were exposed to wide-band noise of 120 dB (Nixon *et al.*, 1966). Differential stimulation of the two ears produced altered disturbances of equilibrium. Similarly, Stevens (1941) found that high-noise levels adversely affected speed of ocular movement and focus and suggested that noise affected the ciliary muscles controlling the lens of the eye. Otolithic stimulation resulted in several specific responses in components of the visual system of cats and monkeys (Gernandt, 1973). Graybiel *et al.* (1972) investigated the vestibular function of one individual whose otolith and semicircular canal function were essentially absent. They found that this subject showed little if any disorientation or abnormal equilibrium and gravitational responses. Apparently the visual, auditory and other senses compensated for normal vestibular function. Cohen (1969) concluded that in normal individuals, while disturbances of vestibular or visual function by infrasonic, sonic, or ultrasonic stimuli may be minute, occupational demands in many environments could make such effects hazardous in terms of human performance or survival.

Based on a review of studies on schizophrenic adults and autistic children, Ornitz (1970) has concluded that central vestibular mechanisms function in more than maintenance of equilibrium during maturation and growth. He suggested that the vestibular system plays a role in modulating the level of sensory input and level of motor output at times of intense excitation. These observations led Ornitz to consider that the characteristic behavioral symptoms of these individuals were suggestive of abnormal states

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of sensory and motor inhibition and absence of inhibition as the result of or associated with vestibular stimulation and response.

In a subsequent study, Ornitz *et al.* (1973) found that vestibular stimulation can increase the amount, variability and clustering of spontaneous rapid eye movement during REM sleep in normal children. He concluded from these data that the vestibular system is involved in mediating the phasic activity of REM sleep. He postulated that the development of central vestibular control over phasic activity during REM sleep followed a maturational sequence and may be related to serotonin metabolism in the central nervous system.

These observations, together with the concept of Guedry (1972) concerning development of reactions to whole body motion during early maturation of children suggest an opportunity for further investigation of the origin of individual patterns of response to motion or infrasonic stimulation in children and adults. It is possible that motion or vibration during early development could be the stimulus for development of several processes of sensorimotor integration and may be related to individual differences in susceptibility to motion.

Rutajaha and Skrzypczak (1974) examined the hearing and equilibrium of workers using ultrasonic detectors in testing railroad tracks for defects. The ultrasonic wavefield is effectively attenuated by air, but because workers use tight fitting earphones, the signal reached the ear canal both directly and via bone conduction. Exposed workers exhibited relatively greater hearing loss, more nystagmus, and more frequent nystagmatic responses with years of exposure. They suggested these effects were due to the pulsed ultrasonic beam acting upon the most exposed vestibular end organ, the saccule. Results of these related but fragmentary studies suggest that the vestibular end organs may be stimulated by infrasonic, sonic, or perhaps ultrasonic frequencies. In addition, the vestibular apparatus, once stimulated by motion, sound or ultrasound, may react by initiation of nerve impulses which affect various higher brain centers. If true, then there is reason to suspect that the vestibular apparatus may have a yet unidentified role in sensorimotor development or function.

B. ELECTROMAGNETIC RADIATION

Lebovitz (1973a; 1973b) noted reports of behavioral and electrophysiological effects of low-level ultra-high-frequency microwave radiation and proposed that absorbed electromagnetic radiation produced thermal gradients in the semicircular canals of the labyrinth. This connective torque induced thermally would mimic natural vestibular stimulation.

Lebovitz (1973a) suggested that caloric vestibular stimulation might occur in man at power densities as low as 35 mW/cm^2, a level far below that thought to induce gross thermal effects. He proposed that this phenomenon might be an alternate source of the reported effects of microwave radiation on the central nervous system (1973b).

Subsequently, Lebovitz (1975) extended his hypothesis to include both the vestibular apparatus and the cochlea. Using minute caloric vestibular stimulation as a model, he proposed that auditory and mixed audiovestibular effects might be related to weak but modulation-sensitive electromechanical effects from microwave radiation pressure and dielectrophoresis. The minute transient thermal gradients in the vestibulocochlear fluids would give rise to sensations of angular acceleration if semicircular canals were stimulated and vibratory or auditory sensations if the utricle and saccule were affected. These concepts are currently under intensive investigation.

IV. SUGGESTIONS FOR FUTURE RESEARCH

Current research programs are oriented primarily toward standardization of experimental techniques and understanding possible adverse biological effects or hazards resulting from exposure to infrasonic, sonic, ultrasonic and nonionizing electromagnetic energies. Presently, little research effort is being directed toward the fundamental aspects of stimulation and response of the auditory and vestibular systems to these forms of energy.

The evidence that the auditory and vestibular systems are sensitive to environmental stimuli other than sound and motion, respectively, is circumstantial and fragmentary; yet there is sufficient data to suggest that these sensory end organs may be activated by such forms of energy. Additional research is necessary to determine whether responses of the auditory or vestibular systems to such stimuli can affect human performance either beneficially or detrimentally.

Suggestions for future research:

- There are persistent reports and observations of altered physiological function and psychological states resulting from direct stimulation of the auditory system by infrasonic energy. In most cases, non-auditory responses probably result from body vibration, but the possible role of the auditory system in these sensory effects should be studied more critically.

- The facts that ultrasound may be a normal speech component, that there are conflicting data on temporary threshold shifts induced by ultrasonic frequencies, and that adverse subjective effects do occur with exposure to ultrasonic stimulation suggest that specific effects of exposure to ultrasonic energies should be studied in man and experimental animals. Critical study of the effects of ultrasonic energy on the basilar membrane, organ of Corti, cochlear hair cells and auditory nerve fibers is required.

- There is a need for additional study of the frequencies and intensities of ultrasound generated by military equipment and their effects upon the auditory system *per se*.

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- Careful study has revealed that microwave radiation results in acoustic stimulation, probably as a consequence of minute thermal gradients generated in cochlear fluid. The existence of auditory system responses to pulsed-modulated nonionizing electromagnetic radiation is in itself significant. Further study of this phenomenon as well as its possible role as a body defense arousal response is necessary.

- Further investigation of the origin of individual patterns of response to motion or infrasonic stimulation in children and adults may clarify the nature of the little-known mechanisms that stimulate development of sensorimotor integration.

- More research is needed on a wider range of nonionizing electromagnetic radiation wavefields with respect to auditory and vestibular stimulation. Thresholds for sensitivity as well as possible deleterious effects must be studied in carefully controlled animal studies prior to additional research on man.

- There is a need to clarify the relationships between effects of nonionizing electromagnetic radiation on the auditory and vestibular systems and the waveform, pulse, and peak power density as well as other characteristics of the electromagnetic energy modulation.

- There is evidence that vestibular stimulation by pulsed ultrasonic wavefields occurs in experimental animals and man. There is evidence to support the hypothesis that vestibular and audiovestibular effects may be related to weak, but modulation-sensitive electromechanical effects from nonionizing electromagnetic radiation wavefield pressure and from dielectrophoresic effects of radiation exposure. If true, the vestibular apparatus may have a greater role in sensitivity to nonionizing electromagnetic radiation such as microwaves than heretofore suspected. There is a need for further study of the transducing system with emphasis on its possible usefulness in information transfer.

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VI. KEY INVESTIGATORS

Alexander Cohen, Ph.D.
Division of Epidemiology and Special Studies
Bureau of Occupational Safety and Health
U.S. Public Health Service
Cincinnati, Ohio 54202

Arthur W. Guy, Ph.D.
Professor
Department of Rehabilitation Medicine
University Hospital
University of Washington School of Medicine
Seattle, Wash. 98195

Allan H. Frey
Random Line, Inc.
Huntingdon Valley, Pa. 19006

Robert M. Lebovitz, Ph.D.
Department of Physiology
University of Texas Southwestern Medical School
Dallas, Texas 75235

Fred E. Guedry, Jr., Ph.D.
Naval Aerospace Medical Research Laboratory
Pensacola, Fla. 32512

Sol M. Michaelson, D.V.M.
Department of Radiation Biology and Biophysics
University of Rochester School of Medicine
Rochester, N.Y. 14642

Edward M. Ornitz, M.D.
Department of Psychiatry
University of California at Los Angeles
Los Angeles, Calif. 90024